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CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY, HARVARD UNIVERSITY.

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During the last six or seven years a large number of d'Arsonval galvanometers, in which the permanent fields are due to hardened and artificially seasoned cast-iron magnets, have been used in the Physical Laboratory of Harvard University, in competition with similar instruments furnished with hardened forged-steel magnets from the shops of well-known makers. For nearly five years also magnets of the same kind have been employed in standard mirror amperemeters and voltmeters fixed in the laboratory, in cases where it was desirable that the indications of the instruments should be trustworthy within one part in a thousand of their larger deflections, over a considerable range of room temperatures. Besides the cast-iron magnets which we have made ourselves, we have of late used a number of others in moving-coil galvanometers purchased in the market — some of the best of them from the Leeds and Northrup Company.

It early appeared from tests made on these instruments, that whereas good iron castings as they come from the foundry make most unsatisfactory magnets, so far as permanence is concerned, magnets made of castings properly hardened and aged after being machined — if machining is necessary for the purpose to which the magnets are to be put — compare favorably in strength, in permanence, and in the relatively small changes of their moments with room temperature, with the best of tool steel magnets, even if in strength, though not in their other qualities, they fall a little behind magnets made, in a forming press, of steel specially prepared for the purpose.

Although chilled cast-iron bar magnets have been used for a long time in a few forms of telephones, it is usually best to make straight magnets (which do not need to be hammered), of steel; but the forging

of steel for permanent magnets of complex forms, without spoiling it, demands a kind of skill which most toolmakers, even in the largest establishments, have not acquired, and it is generally difficult to get satisfactory specimens of any very special shape of curved-steel magnets unless one has access to such facilities as a few of the manufacturers of electrical measuring instruments have provided for themselves. It is true that the hardening of iron castings for magnetic purposes also requires such skill as few persons possess, if the very best results are to be obtained, especially when the pieces to be treated weigh more than a pound or two; but a little practice will enable any good workman, who has a gas forge with blast powerful enough to raise the temperature of the iron uniformly nearly to the melting-point, to make good gray-iron castings of moderate size, hard enough for strong magnets, which will leave little to be desired so far as permanence is concerned. It has been my good fortune to have the help of Mr. G. W. Thompson, the mechanician of the Jefferson Laboratory who has had long experience in treating cast iron, and who has made for me, by a process of his own, massive magnets with extremely low temperature coefficients. It is to be noticed that some of the secret methods of hardening cast iron, used by makers of small parts of machinery, do not fit the castings for making good magnets, and that case hardening, which affects the surface only, is useless. The character of the cold bath into which, while it is kept in violent agitation, the strongly heated castings to be hardened are plunged, seems to have considerable influence upon the result.

At the very high temperature, just under the melting-point, to which the cast iron must be raised before it is suddenly chilled, the metal loses much of its tenacity, and slender pieces must be handled carefully lest they break like chalk. The chilled casting should be hard enough to scratch window glass, if not so readily as hardened tool steel will do it. It is vain to attempt to make any such gray-iron castings as I have used, magnetically hard by chilling them after they have been heated to the comparatively low temperatures that one would use in making steel glass-hard. Everyone who has attempted to harden a thick mass of tool steel uniformly, knows how difficult the task is: it is easy enough to get the outer layers glass-hard, while the interior is much softer; or, sometimes (by overheating the steel), to get the inside hard while the outside is blistered and cracked. If a casting is heated to a very bright red and then plunged into the bath, the outside may become hard to the file, while the interior, as magnetic tests clearly show, remains soft; in this case, however, the material will stand a higher temperature without injury, and

if the mass be reheated and when it is just below the melting point be suddenly chilled, the whole interior becomes hard.

It is a good deal easier to harden a lot of straight, round pieces of good gray cast iron, say 20 centimetres long and 1 centimetre in diameter, so that they shall all be nearly alike magnetically, than it is to do the same with an equal number of pieces of drill rod. Six pieces of Crescent Drill Rod each 16 centimetres long and 8 millimetres in diameter, cut from the same specimen, were made glass-hard for me by a skilled worker in steel; these were placed successively in a properly oriented solenoid and exposed, first to the action of an alternating current of intensity gradually decreasing from an initially high value to a very low one, then to a steady field of 147 gausses applied first in one direction and afterwards in the other. As a consequence of the preliminary treatment * with alternating currents, the magnitudes of the moments acquired by the pieces under the action of the steady field were quite independent of the direction of the latter. These moments were approximately 2280, 2395, 2495, 2326, 2325, and 2360, but when the field was removed the residual moments were 1058, 1074, 1136, 1066, 1050 and 1097 respectively. The same pieces were then placed together in a solenoid made of many turns of large wire and the ends of the whole bundle were connected by a massive yoke; when a current of about 45 amperes was sent through the wire the pieces became charged practically to saturation. When they were removed from the solenoid the average moment of the six was about 1240, the highest 1290, and the lowest 1170. Such uniformity as is indicated by these numbers is, I believe, as great as one can expect to get unless one has an elaborate plant; no such agreement can be hoped for from pieces of different rods of the same brand. Some kinds of special magnet steel give rather better results.

Although it is obvious that there is no advantage in using cast iron for straight magnets, I have had a number of such magnets made, of each of three shapes, for purposes of comparison with steel bar magnets of the same dimensions. These were all rather short, because we had no means of treating satisfactorily very long, slender pieces, which are apt to warp if not properly supported. It is, of course, impossible to calculate the demagnetizing effects of the free ends of such pieces as I have used, but it has seemed to me legitimate to draw some inferences from the hysteresis curves and from the temperature coefficients of rods of different materials if they are geometrically alike.

* J. A. Ewing, Magnetic Induction in Iron and other Metals, 1892, p. 328.

Several years ago, when I had to have a set of the best magnets I could get for measuring purposes, carefully ground into shape after the steel had been hardened, I experimented * upon hundreds of seasoned magnets made of many kinds of steel; ordinary tool steels, self-hardening tool steels, and special magnet steels. In comparing round steels, it appeared that such "Stub's Polished Drill Rod" as I could get made slightly less desirable magnets than did "Crescent Drill Rod," or the common brand of "Jessop's Black Rod," which last two were magnetically indistinguishable. I found nothing better in tool steels than the Crescent Drill Rod, or the Jessop's Black Round Tool Steel, and I have used these as standards in testing my round cast-iron magnets. The subjoined table shows what may be expected of seasoned magnets made of these steels.

Most of my experiments on the strengths of round cast-iron bar magnets have been made with pieces 18 centimetres long and either 0.95 centimetres or 1.25 centimetres in diameter, of which I have a good many, some new and some cast two years ago. These were usually relaxed † after their hardening by being boiled in water for some time; next they were magnetized to saturation in a solenoid, and then they were again boiled and "aged" in the usual manner. The resulting magnets were finally tested in competition with a large number of seasoned tool steel magnets, of different brands but all of the same dimensions as the castings, with the help of a mirror magnetometer. The cast-iron magnets looked, of course, rather rough in comparison with others made of polished rod, but their moments differed among themselves less than those of an equal number of the steel magnets made of any one brand. Just one of the tool steel magnets had a moment sensibly greater (about 4 per cent) than any of the cast-iron magnets, but the average of the moments of the cast-iron magnets was rather greater than those of the steel, even after the records of the two or three steel magnets with abnormally low moments had been rejected.

Two years ago ‡ I measured the temperature coefficients of a good many bar magnets of cast iron and steel. In every instance, as was to be expected, the rate of loss of moment per degree of rise of temperature was much greater at temperatures near the boiling-point of water than at room temperatures, but if for purposes of comparison we used the

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* Peirce, American Journal of Science, 1898, p. 334.

† Barus and Strouhal, Bulletin of the U. S. Geological Survey, No. 14, 1885.

‡ Peirce, These Proceedings, Feb., 1903.

RESULTS OF EXPERIMENTS MADE UPON PIECES OF CRESCENT DRILL ROD AND JESSOP'S BLACK ROUND TOOL STEEL.

Length in centimetres.	Diameter in centimetres.	Weight in grams per centimetre of length.	Moment per gram of magnetism induced in the specimen when placed lengthwise in a unit field.				Permanent magnetic moment per gram of the seasoned magnet.	Approximate ratio of the induced moment caused by unit field, to the permanent moment in the seasoned magnet.	Mean loss per degree of the magnetic moment when the magnet is heated from about 15° C. to 100° C., expressed in terms of the moment at the lower temperature.	Temperature coefficient of the seasoned magnet at 15° C.
			In the condition in which it was purchased.	When "glass-hard" but still unmagnetized.	When magnetized to saturation while "glass-hard."	In the condition of a seasoned magnet.				
20	1.11	7.6	0.44	0.23	0.28	0.30	30.5	0.010	0.00048	0.00047
18			0.41	0.22	0.26	0.28	25.5	0.011	0.00049	0.00048
16			0.38	0.21	0.24	0.25	21.5	0.012	0.00051	0.00050
14			0.34	0.20	0.22	0.23	17.5	0.013	0.00053	0.00052
12			0.29	0.19	0.19	0.20	15.0	0.014	0.00057	0.00057
10			0.25	0.17	0.17	0.18	12.0	0.015	0.00062	0.00062
8			0.20	0.15	0.14	0.15	10.0	0.015	0.00070	0.00070
6			0.15	0.13	0.11	0.11	8.5	0.015	0.00088	0.00087
4			0.11	0.08	0.08	0.08	5.5	0.017	0.00110	0.00109
20	0.95	5.5	0.50	0.23	0.25	0.26	36.5	0.007	0.00040	0.00036
18			0.48	0.23	0.24	0.25	32.5	0.008	0.00046	0.00041
16			0.45	0.22	0.23	0.24	28.0	0.009	0.00051	0.00046
14			0.42	0.21	0.21	0.22	24.0	0.009	0.00056	0.00051
12			0.37	0.20	0.19	0.20	20.5	0.010	0.00063	0.00056
10			0.31	0.18	0.17	0.18	17.0	0.011	0.00071	0.00063
8			0.25	0.16	0.15	0.16	14.0	0.012	0.00078	0.00070
6			0.19	0.13	0.13	0.13	10.0	0.013	0.00086	0.00078
4			0.12	0.09	0.10	0.10	7.0	0.014	0.00095	0.00087
20	0.80	3.9	0.61	0.24	0.24	0.30	41.0	0.007	0.00040	0.00037
18			0.58	0.23	0.23	0.29	36.5	0.008	0.00047	0.00042
16			0.54	0.22	0.22	0.28	32.5	0.009	0.00053	0.00047
14			0.49	0.20	0.20	0.27	26.5	0.010	0.00061	0.00052
12			0.44	0.18	0.18	0.26	24.0	0.011	0.00066	0.00058
10			0.39	0.16	0.16	0.24	20.0	0.012	0.00073	0.00064
8			0.31	0.14	0.14	0.21	17.0	0.012	0.00080	0.00070
6			0.23	0.12	0.12	0.16	13.0	0.014	0.00087	0.00077
4			0.15	0.09	0.09	0.12	8.5	0.014	0.00094	0.00083
20	0.64	2.4	0.69	0.26	0.23	0.25	43.0	0.006	0.00024	0.00020
18			0.65	0.25	0.23	0.24	38.0	0.006	0.00025	0.00020
16			0.61	0.24	0.22	0.24	33.5	0.007	0.00026	0.00021
14			0.56	0.23	0.21	0.23	28.0	0.008	0.00027	0.00021
12			0.49	0.22	0.20	0.22	23.0	0.009	0.00030	0.00023
10			0.42	0.21	0.19	0.21	19.0	0.010	0.00035	0.00026
8			0.33	0.19	0.17	0.18	15.0	0.012	0.00043	0.00030
6			0.25	0.16	0.13	0.15	11.0	0.014	0.00060	0.00039
4			0.16	0.11	0.10	0.10	7.0	0.014	0.00091	0.00049

mean loss, per degree, of the magnetic moment, when the magnet was heated from about 10° C. to 100° C., expressed in terms of the moment at the lower temperature, it appeared that in the case of rods 16 cm. long and 0.95 cm. in diameter these mean losses were

0.00042 for seasoned, chilled, cast-iron magnets
0.00046 for seasoned magnets made of Crescent Steel Drill Rod
0.00046 for seasoned magnets made of Jessop's Round Black Tool Steel

while they were

0.00070 for seasoned magnets made of Jessop's Square Tool Steel 16 cm. long and of cross-section nearly that of the round rods.

In the case of shorter rods the difference was still more in favor of the castings because, I suppose, they were more uniformly hardened in the interior than the steel could be.

If an iron casting which has been hardened and boiled is magnetized in a solenoid either to saturation or to a degree which falls much short of this, it is practically impossible to decrease the moment by even so little as a tenth of one per cent, by striking the magnet on end with a wooden mallet or with a stone. I have tested many such magnets by dropping each two or three hundred times upon a stone slab, or by giving it hundreds of sharp blows with wooden clubs: the magnets get a little warm during this harsh treatment, but when their temperatures again fall to the original point the moments, which may have fallen a small fraction of one per cent, regain wholly, so far as my observations go, their old values. Some few of the specimens of special magnet steel that I have examined are nearly equal to the castings in this respect.

Prolonged boiling has, however, always reduced the moment of the cast-iron magnets very sensibly, and this loss may be as much as 20 per cent when the magnetizing field has been an extremely strong one and the residual moment is very high; if the casting has not been magnetized to saturation, the loss of moment by boiling is much less. If, after a cast-iron magnet has been seasoned, its temperature be suddenly raised from room temperature to 100° C., and then as suddenly lowered, the magnet may not wholly recover its original strength until after the lapse of several hours; if, however, the upper limit be only 50° C., there seems to be no sensible lag in the attainment of the whole of the original moment after the testing.

Most of the steel made specially for magnets, which I have been able to get, has come in the form of long bars of rectangular cross-section, about 2 cm. wide and 1 cm. thick; of such steel I have had pieces, 18 cm. long, hardened in some of the various ways used by professional magnet-makers, to compare with hardened castings of the same dimensions. One of the hardened but unmagnetized castings was placed in a solenoid, exposed to the action of a demagnetizing alternating current, and then put rapidly two or three times through a hysteresis cycle, using a maximum field of 145.2 gausses. After this preliminary treatment — which I used in the case of every piece that I examined — the hysteresis diagram remained unchanged however many times the iron went through the cycle. I first obtained twenty-two points on half the diagram, laid those down carefully upon a piece of coördinate paper on such a scale that the diagram was 41 cm. long, and found that it was possible to draw a smooth curve which would not lie away from any one of the points by so much as a quarter of a millimetre and would apparently pass through almost every point; then I completed the cycle and found that the final reading of the mirror magnetometer did not differ by more than a sixth of one per cent, if by so much, from the initial reading. In the course of its second journey around the cycle, the iron made subsidiary loops on opposite sides of the origin and then returned again sensibly to its original condition. No diagram obtained from a long, slender wire could have been smoother than this one which belonged to this short bar. All the hysteresis curves in this paper are reduced from large drawings; generally about twenty-four points (though sometimes more) were found for each half diagram, and the curve was drawn through practically all of these.

Fig. 1 shows an instance where the points were apparently not so well determined as in other cases. This figure represents hysteresis curves of (A) a piece of hardened cast-iron (18 cm. × 2 cm. × 1 cm.), and (B) of two pieces of Seebohm and Dickstahl magnet steel (of the same dimensions), which makes the strongest saturated magnets of any of the special steels which I have used. The maximum field in the case of the A curve and the larger B curve was nearly 166 gausses, and under this field the cast iron and the special steel acquired moments of about 8900 and 15400 units respectively: when the field was removed the residual moments were about 3120 and 3550. The piece of steel just mentioned was hardened in a water bath; the smaller B diagram was obtained at another time with a similar piece of the same steel chilled in one of the baths used by Mr. Thompson. Although the maximum fields were unfortunately

not the same in the two B diagrams, the general shapes of the curves are very similar.

These two pieces of steel and the cast iron were then placed in the solenoid mentioned above, the ends of each piece were connected together outside the coil by a massive iron yoke, and a current of about 45 amperes was sent through the coil; the residual moments of the cast

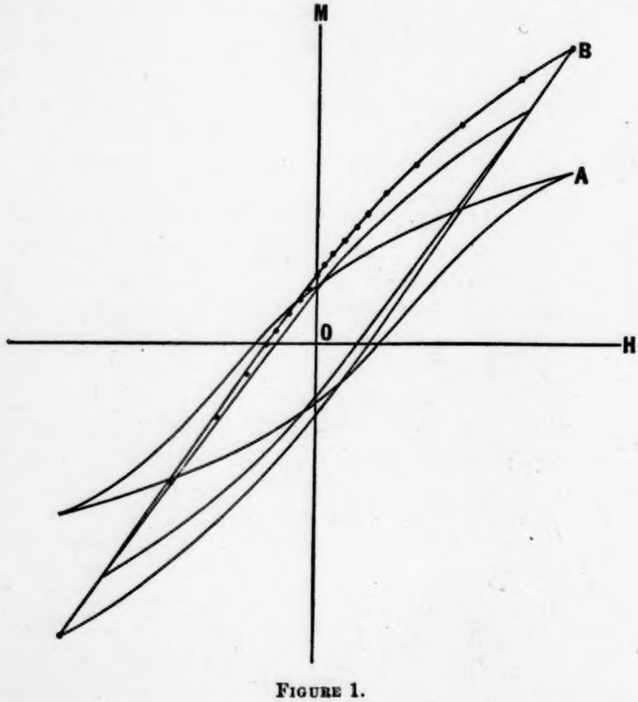

FIGURE 1.

iron, the steel chilled in water, and the steel hardened in the special bath were then about 4390, 5500, and 6220. The weight of each piece of steel was approximately 274 grams. Of three other pieces of steel of a brand used exclusively by well-known makers of magnets for "magnetos," the first was hardened in plain water, the second treated with potassium ferrocyanide, the third chilled in Mr. Thompson's bath. These pieces, like those just described, were 18 cm. long, 2 cm. wide, and 1 cm. thick, and they retained, after being magnetized to saturation,

the moments 3470, 2500, and 4190 approximately: this steel was in our hands, therefore, not so good as the Seebohm and Dickstahl Special. The special magnet steels can be bent or formed, but cannot be heated hot enough for welding without spoiling the material for making magnets.

In Figure 2 the results of observations made by Mr. John Coulson and myself upon round cast-iron rods 18 cm. long and 0.95 cm. in diam-

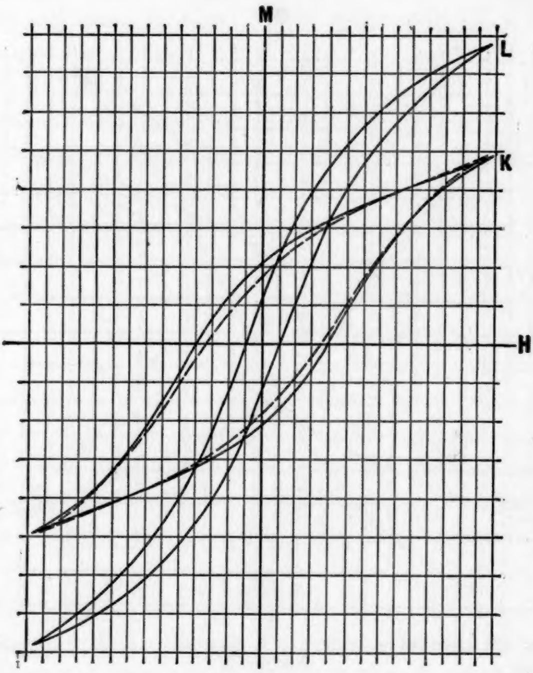

FIGURE 2.

eter are shown. The rods were magnetized in a solenoid, of 4927 turns in a length of 980 millimetres, placed with its axis horizontal and perpendicular to the meridian, and the relative moments, at different times, of the rod under investigation were determined from the deflection of a mirror magnetometer placed outside the solenoid in the Second Position of Gauss with respect to the magnet. The abscissas represent the field (in tens of gausses) to which the rod is subjected by the current in the solenoid, the ordinates represent the corresponding magnetic moment of

the rod in thousands of units. The L-curve was obtained with a soft casting, the heavy K-curve with a casting of the same lot which had been chilled from a high temperature in cold water. At the same time, with this casting, were hardened two or three pieces of Crescent Drill Rod of the same dimensions as it. These were naturally not exactly alike magnetically, but the best of them furnished the dotted K-curve of Figure 2;

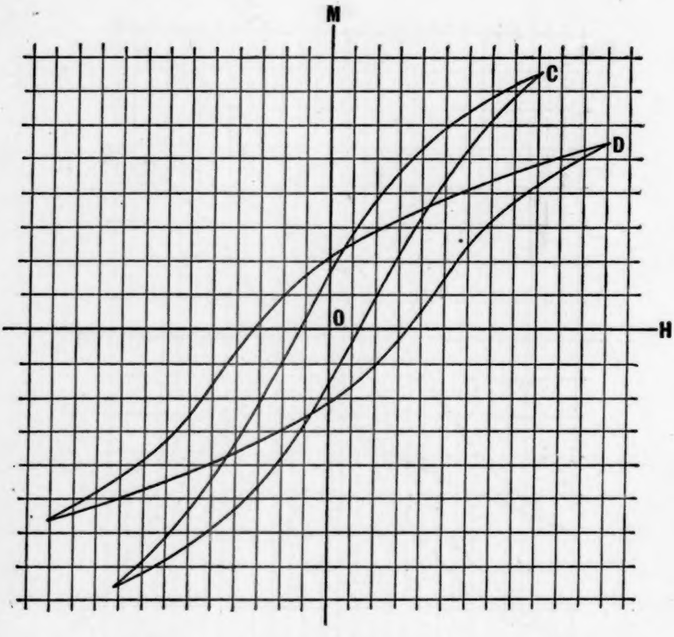

FIGURE 3.

the others had a very little less retentiveness. The magnetic likeness of the cast iron and the steel is worthy of notice.

In Figure 3 the horizontal divisions represent, as before, the field in tens of gausses, the vertical divisions the corresponding moments of the specimens in thousands of units.

The C-diagram was obtained with a soft casting 18 cm. long and .95 cm. in diameter, the D-curve with a casting of the same lot hardened by Mr. Thompson's methods. Another casting of the same set, hardened at the same time, gave the continuous curve in Figure 4, while a piece

of Crescent Drill Rod, treated with the castings, furnished the dotted curve in the same figure. A careful comparison of the curves of Figures 3 and 4, obtained with the chilled castings — which were chosen from the lot wholly at random — will show that they are magnetically almost indistinguishable; the likeness of the Crescent Drill Rod, chosen also at random, to the castings is again shown by the curves of Figure 4.

We have used cast-iron magnets of many different forms, a few of which only are shown in Figure 5; the shapes marked 1, 2, 3, 6 have

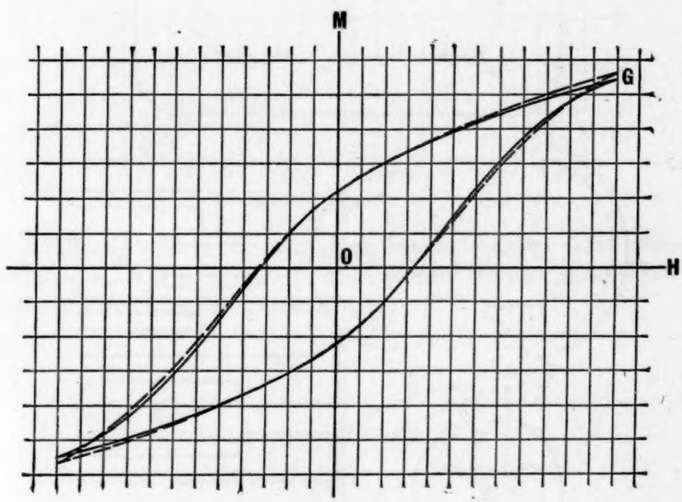

FIGURE 4.

been employed, with the long way of the opening between the poles vertical, in d'Arsonval galvanometers, while a number of rather thin plates of the shape marked 8 have been used together in other instruments of the same kind. Magnets of the shapes marked 5 and 7 produce the artificial fields in some mirror needle galvanometers used as voltmeters.

The mean temperature coefficient (K) between 10° C. and 100° C. of hardened magnets of the shape 1, which weigh 1250 grams apiece, is about 0.00036; K is the mean loss per degree of the intensity of the magnetic field at any definite point between the poles — when the magnet is heated from 10° to 100° — expressed in terms of the field intensity at the point at the lower temperature. For magnets of the shapes 3 and 6 — which weigh 260 grams and 500 grams respectively — K has the values

0.00040 and 0.00031. The actual temperature coefficients at room temperature are always less than these mean values, and in the case of the

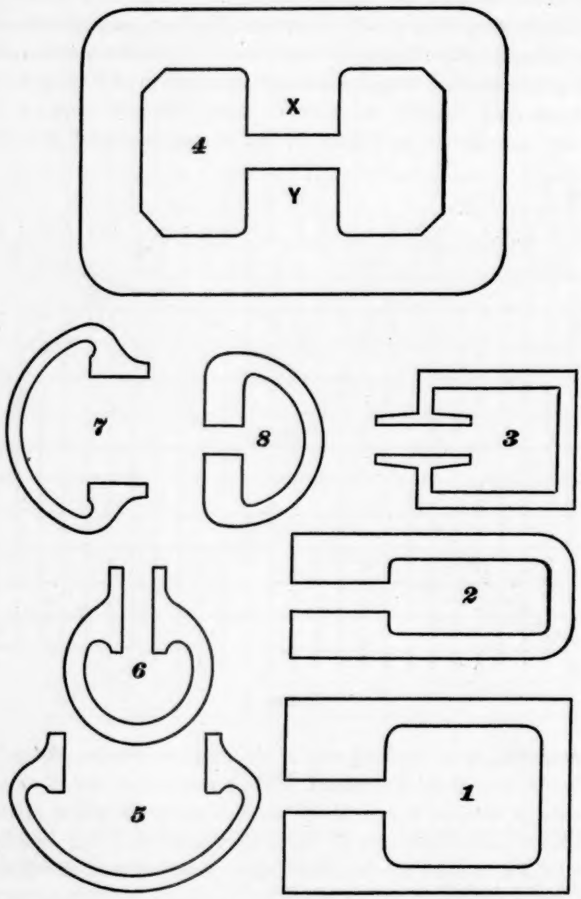

Figure 5.

last-mentioned form the coefficient between 10° C. and 40° C. is not greater than 0.00013.

If the slender part of such a casting as No. 1 be wound as uniformly as possible with insulated wire, and if steady currents of different

strengths be sent through this wire, the relative values of the whole magnetic induction across a given area between the poles can be determined

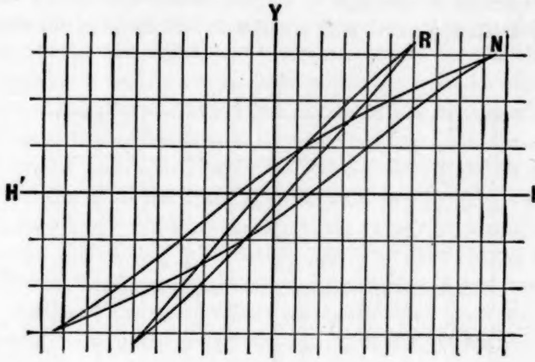

FIGURE 6.

with sufficient accuracy by pulling out, from a definite position between the jaws, a coil of suitable shape made of very fine manganine wire and connected with a ballistic galvanometer.

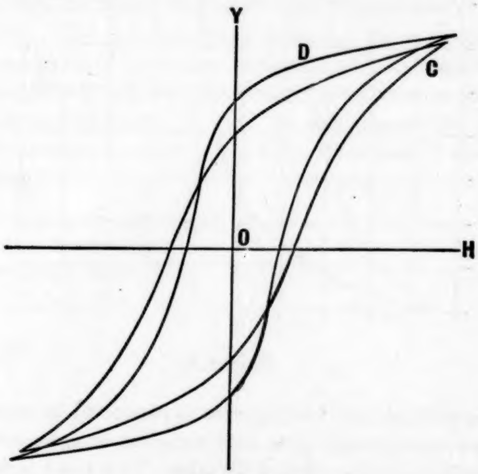

FIGURE 7.

In this way diagrams may be obtained very like the C- and D-curves of Figure 3, according as the casting is soft or hard, and this is a very

delicate method of determining whether a casting which is hard on the surface is also hard throughout the interior. The two halves of each of two thick castings of the shape 4, weighing about 4800 grams each, were wound as uniformly as we well could with 156 turns of insulated wire,

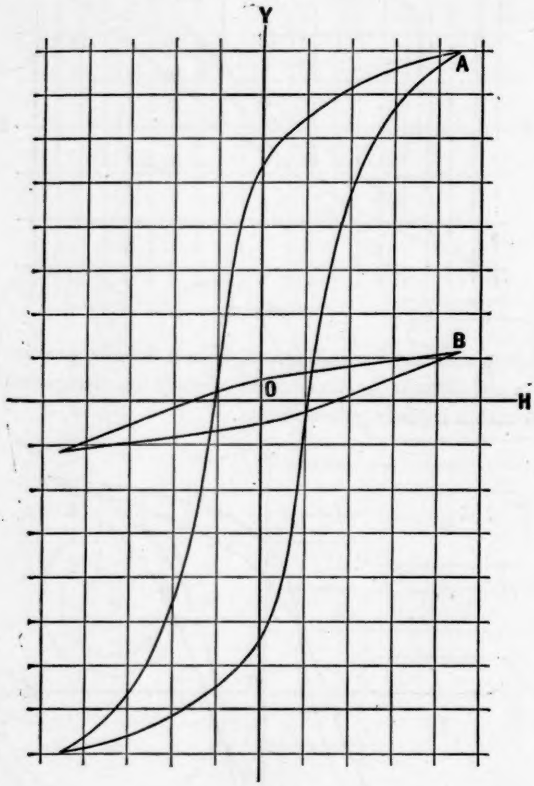

FIGURE 8.

and the two coils of each casting were so connected in series that when a current was sent through them both conspired to make one of the projections (say X) a north pole and the other (Y) a south pole: one of the castings was soft while the other, as another experiment afterwards proved, had been imperfectly hardened. With each of these castings a rough kind of hysteresis diagram was obtained by measuring for different

current strengths the induction flux in the air between the poles; the ordinates in Figure 6 represent, in hundreds of lines per square centimetre, the induction across the centre of the gap X Y, while the abscissas represent the current in the coils measured in amperes; the R-curve belongs to the soft and the N-curve to the supposed hard casting. In a second experiment made with the same castings, one of the coils on each was used as a primary and the other, which was connected with a ballistic galvanometer, as a secondary; this procedure gave the curves of Figure 7, which show clearly that the second casting, which was very hard to the file on the surface, was still soft inside. The diagrams of Figure 8, drawn on a different scale, give the results of a similar experiment on the soft casting just mentioned and a third chilled casting of the same form. These striking curves, which were reduced from a large drawing, represent the observations accurately, and illustrate the fact that it is possible to make the whole inside of a massive casting, like the one here used, magnetically very hard.

When the gap X Y of this third casting had been closed by a piece of soft iron, and a heavy current had been sent through the coils for a few moments, in such a way as to make one of the projections a north pole and the other a south pole, the casting became a fairly strong permanent magnet: the flux per square centimetre across the middle of the air gap was finally 285. The flux per square centimetre across the gap of a similar, though considerably less heavy, hardened cast-iron magnet, belonging to one of a number of excellent d'Arsonval galvanometers furnished by Messrs. Leeds and Northrop, is 187. In this magnet the pole projections are a little shorter and the gap a trifle wider than in the castings 4 described above.

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